NDE Inspections and Lifetime Assessment of Turbine Equipment

Power-Gen International 2008 – Orlando, FL
December 2-4, 2008
NDE Inspections and Lifetime Assessment of Turbine Equipment

Waheed Abbasi, Ph.D., Principal Engineer
Sazzadur Rahman, Ph.D., Materials Engineer
Michael J. Metala, Mgr. Siemens Technology and Inspection Services

Siemens Energy, Inc., 4400 Alafaya Trail, Orlando, FL 32826-2399

Abstract

The growing demand for power is putting tremendous stress on existing power plants for generating electricity. The plants are being operated for longer periods of time under heavy load conditions. Reliability of key components of the power plant such as steam or gas turbines and generators is of prime importance. Many utilities are interested in extending the life of turbine-generator components to reduce costs while maintaining safe operating conditions. Turbine rotors being operated past their anticipated design life objectives are of special concern. Life assessment studies must have metallurgical and non-destructive testing evaluations to help assess the suitability, if any, for the continued operation of the component. Conventional nondestructive testing such as visual and magnetic particle inspection can be used for surface assessment while ultrasonic testing as well as phased array ultrasonic testing can be used for internal assessments. Phased array ultrasonic inspection of critical areas such as blade attachments and blade roots allows the inspection to be performed without removal of blades. Information obtained from both NDE and metallurgical assessments is combined with engineering evaluations to perform an effective life assessment of components. Using unit operational information and NDE tools, combined with metallurgical data gathered on service components, provides a comprehensive assessment allowing users to make informed judgments regarding potential further safe and reliable operation of critical power plant components.

1. Introduction

The tremendous demand for the power in today's world is pushing the power generation industry to continue operating their existing aging units. As a result the remaining life assessment of these aged units is becoming important for continued safe and reliable operation. Among the factors that determine the lifetime of turbines are the strength and reliability of components that are exposed to high temperatures and pressures. Many older units have exceeded their anticipated design life objective. Most of the turbine components are made of steels with addition of different alloying elements such as chromium, vanadium, nickel, molybdenum, titanium etc. During operation, these materials undergo different metallurgical degradation processes due to high stress, creep, fatigue etc. So, remaining life assessment of these components/materials is essential for the lifetime extension of these aged units through repair work, continuous inspection, replacement of the degraded parts, etc [1].

Siemens has established a Lifetime Assessment (LTA) (sometimes referred to as Lifetime Evaluation (LTE)) program to support the goal of continued safe and reliable operation with increased output and efficiency of aged units in North America. This paper describes different aspects of lifetime assessment using nondestructive evaluation (NDE) techniques as well as metallurgical evaluation methods for steam turbines (ST), gas turbines (GT) and balance of plant (BOP) components.

2. Failure Mechanisms in Turbine Components

In service exposed power plant components there are several different damage mechanisms that determine the remaining life of the service components. Among the most common possible damage mechanisms in the materials of turbine components are:
Creep
- Fatigue (high cycle and low cycle)
- Creep-Fatigue interactions
- Thermal Aging (carbide coarsening/inclusion growing)
- Corrosion
- Stress Corrosion Cracking
- Mechanical Damage (erosion)

The major mode of mechanical damage initiation occurs due to the creep and low cycle fatigue (thermal fatigue). Environmental assisted cracking and stress corrosion cracking are also important modes of failure due to the presence of different gases in the turbine. A majority of the turbine components are exposed to high temperatures and high stress conditions during operation and as well as during start up and shut down. In the case of low pressure turbines moisture exposure coupled with high stresses can lead to stress corrosion cracking.

Even though considerable attention is given to materials selection during the design of these components, as a result of manufacturing processes as well as service induced stress, there is a possibility of failure within the anticipated design lifetime. Therefore, periodic maintenance and inspection, as well as continued adherence to OEM standards are necessary to avoid unexpected failures in power plants.

3. LTA Methodology

Lifetime assessment of power plant components involves a variety of approaches to obtain comprehensive knowledge of the service component condition. The main tools available are:

1. Nondestructive Evaluation for Flaws/Cracks
2. Metallurgical Evaluation for Materials Properties Degradations
3. Computational Method for Fracture Mechanics Analysis

3.1 Nondestructive Evaluation (NDE) Methods:

NDE is a well established and proven tool to help determine the integrity of steam turbine, generator, and gas turbine components during their life cycle in power plant environments. Conventional methods such as penetrant testing (PT) and magnetic particle testing (MT) are well suited to detect surface and slightly subsurface discontinuities. These methods are particularly sensitive to small surface service induced cracking in various components. Penetrant testing, which requires the discontinuity to be open to the surface for detection and magnetic particle testing can only be used on magnetic materials. Visual inspection (VT), performed either with the human eye or with high-resolution cameras, is limited to dimensional measurements, usually the detection of large open discontinuities or component condition assessment. Longitudinal and shear wave ultrasonic testing (UT) is used for full volumetric interrogation of a component while eddy current testing (ET), an electromagnetic method, is sensitive to small surface or slightly subsurface indications in many materials. Radiography testing (RT), using X-rays or gamma rays is useful for detecting internal indications in welds, pipes, and a host of other components.

In addition to the conventional methods of NDE, there are specialty methods that have been developed by Siemens to provide improved inspection capabilities and better results that assist in the LTA and LTE process. Some of these methods are discussed below:

3.1.1 Acoustic Thermography

Several NDE methods exist to inspect steam and gas turbine blades. Depending on the OEM blade design and the location of stresses, a particular NDE method is selected that best addresses the area of inspection concern. Often conventional methods such as MT, ET or UT are used to interrogate the blade for service induced cracking. In most cases these methods are adequate to detect the indica-
tions of interest. Siemens Acoustic Thermography [2] is a new method being successfully employed for detecting tight cracks and other service damage in turbine blades and other turbine components. Figure 1 is a schematic of how the technology functions. A high energy, low frequency source is used to energize the component. The energy entering the part causes vibration. In simple terms, if a crack is present the faces rub against each other and generate heat as a result of the vibration. A high resolution, high-speed infrared camera monitors the part and detects the heat generated from the discontinuity.

A special computer imaging system is used to observe the part and capture the infrared inspection. The data acquisition system captures approximately 2 seconds of video of the test part and any subsequent thermal image that occurs. This information is stored in a video format file. Relevant indications glow brightly and then disappear as the heat dissipates during the two-second time frame. The method is more sensitive to tight cracks and discontinuities and less sensitive to open flaws. Unlike other methods such as ultrasound and eddy current testing that rely on electrical discharge machine (EDM) reference notches to simulate flaws, acoustic thermography is not well-suited to detecting these types of artificial discontinuities because little heat is generated from them. The technology has several significant advantages over more common inspection methods. In the case of gas turbine blade configurations, the entire blade can be inspected in a single setup. Both the root and airfoil can be viewed for small cracks during the short two-second thermal cycle. Of particular importance is the ability of the method to see relevant indications through protective coatings that are applied to combustion turbine components. Small indications are easily found emanating from cooling holes in vanes and blades without the need to strip the coating, as would be the case for penetrant and at times eddy current test methods.

### 3.1.2 Ultrasonic Phased Array

Siemens has been developing ultrasonic phased array techniques to reduce inspection times and improve data evaluation for a variety of turbine components. These techniques include methods for inspecting Westinghouse design LP disc bores and other manufacturer design disc bores. To assess the condition of the blade roots, techniques have been developed that allow the highly-stressed areas of the blade root to be inspected in situ, i.e. without removing the blades. Similarly, phased array methods are in place to detect stress corrosion damage in blade attachments while the blades are installed in the turbine disc (in-situ examination) [3].

It is extremely important that the inspection methods that are developed accurately address the requirements of the ultrasonic examination. To fulfill this need the inspection process is modeled using a variety of methods and is then tested and validated. These methods must include the modeling of the inspection component geometry and phased array energy to develop accurate control (focal) laws. In addition, the methods must include means of determining the behavior of the incident beam as well as the behavior of the reflected beam [4]. The modeling of the beam is even more critical when dealing with a compound curvature considering the effect the surface has on the sound beam. In the case of a continuously changing surface with complex geometry, there are instances when the curvature is positive in one direction and negative in another. This affects the sound beam differently and has to be modeled to get a sensible and accurate set of focal laws for an examination.

![Figure 1: Schematic of Acoustic Thermography System](image)
Developing accurate focal laws is the first step in formulating a technically sound inspection methodology. The next step is determining the sound field that is transmitted and verifying that it is available at the area of interest. This is done by simulating the field of the beam at the focal depth and determining the quality of the sound that is available for reflection. Based on this information important decisions can be made regarding the scanning strategy of the area of interest. This step is only one side of the coin, though. What is also important is the determination of the quality of the signal received back at the transducer from the area of interest. There are various methods of accomplishing this. A traditional method is testing this experimentally and evaluating the complete exam on test specimens. While this method is ideal, it may not be a feasible or realistic method for reasons ranging from availability of sample specimens to the time and cost involved. Another approach is the accurate simulation of the examination and then analysis of the results. This provides enough information to devise a scan strategy with the confidence that the results obtained are meaningful and reliable.

Figure 2 illustrates the simulation of focal laws on blade attachments and disc bores respectively. The laws are developed using a CAD model so it is representative of a true 3D space. No matter what the application, when dealing with complex geometry, simulation of laws provides a valuable mechanism for determining the accuracy of the laws and provides feedback to optimize the scans. Further, once the focal laws are developed for a desired scan, analysis is required on the beam properties to ensure the validity of the focal laws. The field diagram provides information about the sensitivity of the sound beam at the focal point and is a feedback tool for the user to vary the scan strategy. As is obvious from the above discussion, these modeling and simulation tools are of prime importance in establishing sound and thorough inspection methods.

### 3.1.3 Rotor Bore Inspections

Many units in service have rotating equipment (rotors) that have bores in them. These rotors were manufactured in an era when forging techniques were not as sophisticated as today’s methods and which sometimes may have resulted in impurities and inclusions migrating towards the center during the forging process. The solution at that time to address these imperfections was to machine a bore through the center to remove centerline impurities and to help minimize the chance of crack initiation that had the potential of contributing to a rotor failure. While this offered an effective solution, there was always a chance that some area around the bore would include some discontinuities linking together as a result of service operation. To help prevent potential failure due to existence of such discontinuities, inspections are performed on the bore surface, near surface, and deep surface to detect these indications. These inspections include a variety of methods including magnetic particle testing, eddy current testing, and ultrasonic testing.

These tests are performed to detect cracking from service stress as a result of forging discontinuities. Often, a mechanical test to measure the bore diameter is performed. Accurate bore
measurements can be used to detect the presence of creep damage. In addition, either eddy current inspection of the bore surface or magnetic particle inspection is performed. For sub-surface indications, multi-channel ultrasonic inspection is performed. To perform the eddy current and the ultrasonic inspection, sophisticated automated scanning systems developed by Siemens are used. These systems provide information regarding the location of the discontinuity while the inspection method provides information related to the discontinuity itself. The data collected is then analyzed to determine the rotor condition. The data is further used, in conjunction with other information, to assess the remaining life of the rotor for safe operation. This provides a reliable tool to the plant operators to keep equipment operational in a safe and cost-effective manner. The scanning systems (Figure 3) play an essential role in the successful application of this inspection. The ability to control the various parameters such as scanning increments, data resolution, provides flexibility to the inspector.

3.1.4 High Temperature Video Inspections

Unit availability is an essential component for electric utilities to be successful in the operation of a power plant. When components experience an event that causes the unit to be forced out of service it is important to identify the condition and address it quickly allowing the unit to go back on line. Siemens has innovative tools which have been developed to enable personnel to respond quickly, including the means to begin a visual assessment of the unit condition even though unit internal temperatures are close to 1000°F (538°C). A high temperature borescope system has been developed and is being successfully implemented at utility sites across the Americas. The system allows the insertion of a high-resolution videoprobe camera into the gas turbine unit through available access ports and holes in order to begin to diagnose the condition. Although the video camera is entering a “hot” unit the camera head is cooled to temperatures as low as 70°F (21°C). This allows inspectors to stay outside the unit near the hot opening as long as needed to fully examine unit components. The high temperature system has been used continuously for durations of up to one hour. Commercially available video probes can only survive in temperature environments less than 180°F (82°C) and for much shorter periods of time. Figure 5(a) shows the high temperature borescope inserted into an access port of a combustion turbine unit. The system

![Figure 3: Rotor Bore inspection scanner testing on a calibration rotor.](image)

![Figure 5: (a) High temperature borescope in use; (b) right side shows an indication as seen by the borescope.](image)
allows video images to be captured like that shown in Figure 5(b). Condition information obtained from this visual inspection allows engineers to address the cause of the forced outage and begin to plan a strategy to quickly bring the unit back up on line.

The high temperature videoprobe system has been successfully used to inspect some non-Siemens high pressure (HP) steam turbines with special designed access ports. A much longer high temperature videoprobe system is currently being developed to allow inspection of HP turbine internals and control stage blades (buckets) where inspection distances exceeding 20 feet (6m) are required for insertion through control valves or balance hole-openings.

3.2 Metallurgical Damage Evaluation

Many of the power plant components such as turbine casing, valves, rotors, blades, bolts etc. operate at high temperatures. As a result, creep damage occurs on these components due to the exposure to high temperature and stresses. There are several metallographic techniques that have been developed to evaluate creep damage by using the correlation of microstructure of the original material to the serviced material and also by using hardness measurements.

Replication method: Microstructural degradation occurs due to creep damage in the following forms: The microstructure of the materials that is exposed at high temperature shows a change in the microstructure by forming a void at the grain boundaries or evolution of carbides at the grain boundary. Investigation of formation of voids is a very common practice [in the European region] for evaluating creep damage. Creep damage starts by forming a void at the grain boundary and as the damage accumulates the cavities increase in size and gradually forms micro cracks and eventually fails by rupture. In steels, due to the presence of different elements, different carbides form due to exposure at higher temperature and these carbides precipitate intergranularly as well as intragranularly. Also the carbides tend to increase in size as they are being exposed to high temperatures, eventually softening the materials. By taking a replica of the microstructure this damage can be evaluated.

Hardness method: The hardness of any material is reduced as it undergoes different degradation modes caused by creep-fatigue as a result of high temperature exposure for a long period of time and high stress condition during start-ups and shut-downs. It was first proposed by Goldhoff et. al that hardness value can be used as a nondestructive method to evaluate creep damage. There is a correlation between the hardness values to the lifetime assessment of any components. The hardness of materials changes with aging time, temperature, and stress, and as a result hardness decreases with exposure to creep. Thus, by measuring the hardness of any component it is possible to extract information that assists in evaluating the remaining life of the component.

Figure 4: The temperature distribution of the valves during steady-state operation on the basis of an initial steam temperature of 538°C.
3.3 Computational Method (FEA)

One of the key components in lifetime assessment is to use computational methods to calculate local material temperatures, local stress levels and their direction at critical areas of the components. Turbine components are operating in a temperature range where the creep mechanisms are under steady state stress and the material is exposed to thermal cyclic stresses as a result of transient operations. These combined creep and thermal stresses which in turn are responsible for low cycle fatigue over operational time are principal degradation mechanisms which can lead to crack initiation and growth. Hence, during finite elemental analysis of these components both steady state and transient loading has to be considered. The critical factors for a meaningful component analysis are the basic design data and appropriate boundary conditions like thermal convection and radiation, mechanical restrains or contacts during operation. Figures 4 and 5 show an analyzed steady state temperature and stress distribution of a steam turbine valve.

![Figure 5: The equivalent stress distribution of the valves in non relaxed state.](image)

4. Turbine Component Assessment

4.1 Steam Turbine LTA

Siemens has more than 20 years of experience in assessing the lifetime of steam turbine components. During operation, highly stressed components of steam turbine power plants undergo a change in material properties due to cyclic stress and exposure to different temperatures. Sometimes, as a consequence of these changes during service, crack initiation may occur and eventually can cause certain components to fail. To evaluate the remaining lifetime of any component one has to consider the operation history of the unit as well as the material properties. Among the main components that have to be evaluated during the LTA are turbine casings, valves, pipes, rotors (turbine and generator) disks, retaining rings, bolts etc. The areas most affected by high service stresses and temperatures in the steam turbine are shown in Figure 6.
4.2 Combustion Turbine LTA

Life of gas turbine components is limited due to the exposure to stress caused by temperature or static and dynamic loading like creep, low-cycle fatigue (LCF) and high-cycle fatigue (HCF), erosion, corrosion, oxidation and mechanical stress, wear, and damage due to vibration. The major limitations for service life comes from the load capability of the components that are exposed to the highest stress or temperatures. The LTA program targets normal modes of service degradation such as damage due to creep, low and high cycle fatigue and for crack propagation. During LTA of gas turbines, usually the non-consumable components such as combustor inspections or hot gas path are typically inspected. Lifetime assessment requires a detailed inspection be performed to find the evidence of any kind of material degradation such as creep and fatigue damage, material softening and degraded material properties. It also takes into account the gas turbine unit-specific analyses, machine history and findings. Based on the findings from the LTA, Siemens provides modernization and upgrade options to allow the operator to
replace components or to enhance the capabilities of the unit. Figure 7 shows typical degradation modes for different component in a gas turbine. Figure 8 shows an automated scanner inspection of combustion turbine disc.

4.3 Balance of Plant (BOP) LTA

Other than the turbines and generators, power plants contain many components that are highly stressed either due to mechanical motion, exposure to temperature and/or pressure, or a combination thereof. Components such as valves and steam piping are amongst these highly stressed components that have to be inspected and evaluated to determine their integrity. This process involves the nondestructive evaluation of these components and analysis of these results. If any reportable indications are found, they are evaluated further using appropriate LTA tools. This information combined with operational data can provide the material state of the components and aid in decisions regarding the continued safe operation of the power plant.

5. Summary

Life Assessment of power plant components has gained significant importance in the past decade as the power plants have aged and newer technologies have become available for inspection and evaluation of these components.

Use of advanced NDE techniques for inspection of power plant equipment plays a key role in helping the users to evaluate the condition of plants. This evaluation aids in the safe operation of plants. Additionally, these techniques provide information that assists in the lifetime assessment of power plant components.

A variety of NDE techniques have been developed and are being continually developed to best inspect the components and provide a more accurate representation of material condition.

Each component in the power generating equipment requires appropriate nondestructive evaluation and further analyses based on the results obtained from the NDE. These evaluations coupled with the operating history and material history of the components provide the basis for lifetime analyses.

The clear objective of the LTA process is to assist the users to evaluate the potential for continued safe and efficient operation of the power plant and providing the possibility to detect and address potentially debilitating damage before it may occur.

Permission For Use

The content of this paper is copyrighted by Siemens Energy, Inc. and is licensed only to PennWell for publication and distribution. Any inquiries regarding permission to use the content of this paper, in whole or in part, for any purpose must be addressed to Siemens Energy, Inc. directly.

References

